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TEST OF PERIODICITY IN THE QUASAR OJ 287

RICHARD B. STOTHERS[1] AND AIMO SILLANPÄÄ[2]
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ABSTRACT

OJ 287 displays an apparent periodicity in its violent optical light variations. By applying a progressively brighter faint-magnitude cutoff of the data when performing time series analyses of the light curve, the best-fit period is found to increase from 11.7–12.1 yr (depending on the method used) to 12.4 yr (based on an analysis of only the times of light maximum). In comparison, the average time interval between large outbursts is 11.7 yr. The derived period exhibits noticeable instability, which cannot be caused by the very slow modulation of the light curve or by the double-peak structure of the light maxima. Moreover, the probability of obtaining such a periodicity by chance in the 105 years of past observation is at least 0.02. Nevertheless, arguments based on the observed repetition of structure in the light curve, combined with a binary black hole model, suggest that a real underlying periodicity does exist.

Subject headings: black hole physics — BL Lacertae objects: individual (OJ 287) — quasars: individual (OJ 287)

1. INTRODUCTION

OJ 287 belongs to a small subgroup of quasars known as BL Lacertae objects or blazars. Although its extreme optical variability displays an apparent 12 yr periodicity (Sillanpää et al. 1988, 1996; Kidger, Takalo, & Sillanpää 1992), the statistical significance of the proposed periodicity has never been estimated rigorously. Among the methods used to determine the value of the period, two fall into the category of Fourier analysis techniques (Warner & Robinson 1972; Deeming 1975) and a third belongs to folding methods (Jurkevich 1971).

To examine this problem further, we apply here two other techniques: linear spectral analysis based on the assumption of a series of periodic delta-function light pulses, and circular spectral analysis based on the assumption of a continuous sinusoidal variation of the light (Stothers 1991). Both methods can also be applied to just the observed times of light maximum. In the latter case, it becomes possible to estimate the statistical significance of the proposed period in a rigorous and unbiased fashion. OJ 287 is a very important test case for quasars, because it has probably the best observed light curve for any quasar.

2. DATA

The observational data for OJ 287 consist of photographic and photoelectric B magnitudes secured between the years 1891 and 1996. They have been described elsewhere (Takalo 1994) and are updated here. Typical observational errors for data acquired before 1972 on archival photographic patrol plates are ± 0.15 mag, but the errors since then have been reduced to less than ± 0.05 mag. Following Sillanpää et al. (1996), we have averaged the observed magnitudes in 7 day bins in order to achieve a compromise between the fine time resolution needed to see the brief pulses and the obvious need to lessen the relative weight of the very abundant data acquired during the last two decades. Despite this compromise, the historical light curve is far from homogeneous and stationary, as Figure 1 shows. In addition to the presence of many gaps in the early years, the maxima of the light curve fluctuate slowly, with the largest maxima occurring around 1913 and around 1972. The three most accurately resolved outbursts (during the 1970s, 1980s, and 1990s) contain a double-peak structure, the separation of the two peaks being 1.1–1.2 yr. The peak that follows is slightly fainter than the leading peak.

3. METHODS

Linear spectral analysis (LSA) performs a fit of the observed time series to a series of periodic delta-function pulses, rather than (as in Fourier methods) to a series of circular trigonometric functions. To obtain a useful rms residual, the amplitude of an observation at a given time is used to weight the square of the difference between the observed time and the nearest predicted time. If only the observed times of maximum are employed in the analysis, the method reduces to a modification of the Broadbent (1955) technique of point series analysis.

Circular spectral analysis (CSA), on the other hand, assumes a continuous sinusoidal function of time, weighted by the data amplitude at a given time. It employs formulae that are identical to those developed long ago for least-squares sine-wave analysis in its lowest order approximation. By using only the observed times of maximum, one recovers the familiar Schuster–von Mises technique of circular statistical analysis for directional data.

In practice, both the LSA and CSA methods produce normalized frequency-plot spectra that are nearly identical to one another (Stothers 1991). The reason for this very close similarity is that a *singly* periodic function is being fitted to the observational data at each trial frequency.

4. PERIODICITY SEARCH

Initially, the two methods were applied to all of the B-magnitude data, including both times and amplitudes, falling between the years 1891 and 1996. The basic period found is then 11.7 yr, but the spectrum appears very noisy and the correct period can be securely identified only after further analysis based on some pruning of the data, as described below. Another complication is that all trial periods longer than $\sim$30 yr artificially appear to be highly significant and so

[1] Institute for Space Studies, NASA/Goddard Space Flight Center, 2880 Broadway, New York, NY 10025.
[2] Tuorla Observatory, University of Turku, FIN-21500, Piikkiö, Finland.

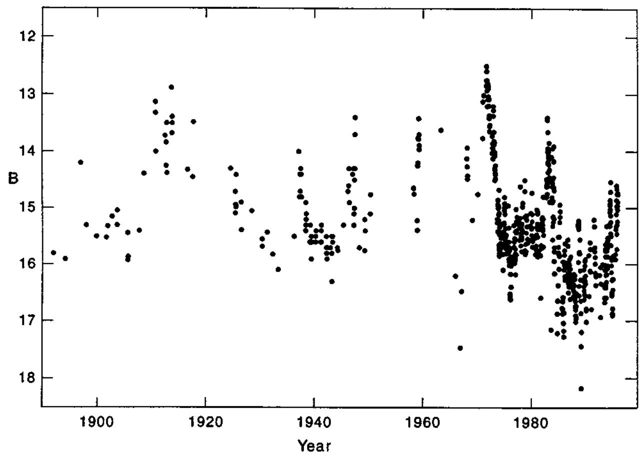

FIG. 1.—*B*-magnitude light curve of OJ 287 over the time interval 1891–1996.

are not statistically distinguishable from each other. In contrast, both the Jurkevich folding method and the Fourier analysis methods, by more accurately fitting the complex light curve, resolve the very long periods and show formal evidence of an additional period of ∼54 yr, arising from the light-curve modulation (Kidger et al. 1992; Sillanpää et al. 1996). The record length, however, is only 105 yr, and so this period remains in some doubt.

To circumvent the problem of the confusing complexities in the light curve, we have next eliminated all of the data points fainter than a certain limiting B magnitude. In other words, we have retained only the brightest phases of OJ 287. The faintest allowed magnitude was first taken to be $B = 15$ and then $B = 14$. With $B \leq 14$, we are viewing primarily the pulse peaks (though not all of them, because the 1994 pulse peak and the partially sampled 1896 pulse were fainter than $B = 14$). For these two reduced data sets, the basic periods become 11.8 and 12.0 yr, respectively.

The foregoing time series analyses were repeated by adopting only the more adequately covered years 1931–1996. The derived results turn out to be only slightly different from those based on the 1891–1996 time series.

In the limit of extreme data pruning, only the seven times of peak light were used for the analysis. Six of these known epochs are listed in Table 1 of Sillanpää et al. (1988), to which we have added the most recent epoch, 1994.9. Successive intervals between the observed maxima are approximately 24, 10, 12, 13, 11, and 12 yr; probably there was an unobserved maximum in 1925, which would account for the unexpectedly long 24 yr interval. For this reason, we have next truncated the time series to include, as above, only the years 1931–1996. For both the truncated and the untruncated time series the basic period found is 12.4 yr.

Note that as the data are progressively pruned, the basic period increases monotonically from 11.7 to 12.4 yr. This curious sequence reveals the hidden (and unwanted) influence on the period searches arising from the very abundant observational data contained between the major outbursts. Of equal interest is the fact that the analysis of the times of light maximum yields a substantially longer period, 12.4 yr, than the simple average time interval between light maxima, which is 11.7 yr. The reason for the difference is that the average time interval is a biased quantity, being constrained by the values of

TABLE 1

RESULTS OF TIME SERIES ANALYSIS OF OJ 287

YEARS	B (mag)	N	P (yr) LSA	P (yr) CSA
1891–1996......	All	658	11.7	11.6
	≤15	193	11.8	11.9
	≤14	74	12.0	12.0
	[a]	7	12.4	12.4
1931–1996......	All	619	11.5	11.1
	≤15	170	12.0	12.0
	≤14	63	12.2	12.2
	[a]	6	12.4	12.4

[a] Used only the observed times of maximum light.

the endpoints of the defining time series and by the total number of intervening light maxima. A summary of our principal results for the period, P, is contained in Table 1, where N represents the number of observations used.

The frequency-plot spectrum derived for the six times of light maximum between 1931 and 1996 is displayed in Figure 2. The plotted measure of goodness of fit, $S(f)$ for trial frequency f, represents a constant quantity minus a dimensionless rms residual (Stothers 1991). The prominent spectral peak centered at 12.4 yr shows a smaller peak at 11.0 yr on its shoulder. But only the central peak yields a noticeable first harmonic. Sillanpää et al. (1996) had previously detected these two close peaks, and had attributed the bifurcation either to an instability of the basic period or to the observed double-peak structure of the large outbursts. It is now possible to rule out the latter interpretation, because our present analysis uses only *one* time of maximum for each large outburst. In fact, if the times of *both* maxima for each of the three most recent large outbursts are used, the derived results do not change materially, since the time separations of the component peaks are so small.

Using the Jurkevich folding method, Kidger et al. (1992) determined a best-fit period of 11.6 ± 0.5 yr from all the data up to 1991. This is to be compared with the present value of 11.7 yr based on nearly the same data set. In a study that

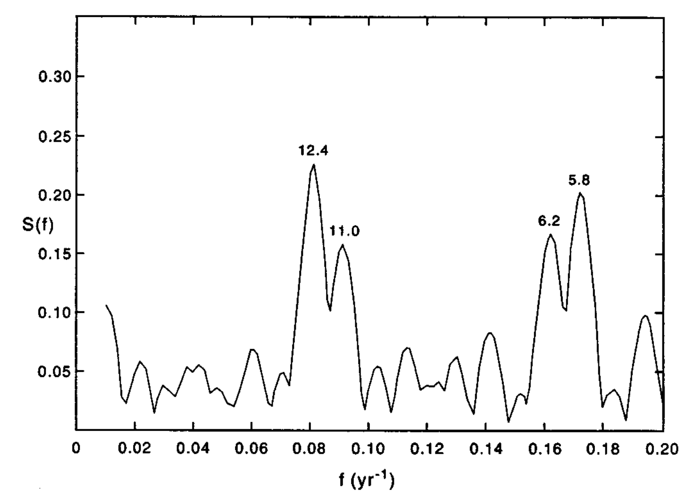

FIG. 2.—Frequency-plot spectrum, obtained from linear spectral analysis of the six times of light maximum of OJ 287 between 1931 and 1996. $S(f)$ is a measure of the goodness of fit, as defined in the text. Periods of major spectral peaks are identified.

utilized a Fourier analysis technique, Sillanpää et al. (1996) obtained 12.1 yr, but they pointed out that the derived period varied slightly (11.7–12.2 yr) depending on how the data were binned. We have demonstrated that variable relative weighting of the pulse phase and interpulse phase from cycle to cycle (due to sampling fluctuations) also exerts a substantial influence on the derived value of the period. Nevertheless, it is comforting to find that a detailed treatment of the whole light curve (Fourier analysis with a CLEANed spectrum) gives very nearly the same period as does a more direct analysis of just the observed times of light maximum.

5. STATISTICAL SIGNIFICANCE OF THE PERIODICITY

Sillanpää et al. (1988) estimated the statistical significance of the discovered periodicity by taking the basic period to be the average time interval between outbursts and by then calculating the probability of obtaining by chance the small amount of scatter of the observed times of maximum around the predicted times. In this way they found a probability of 8×10^{-5}. Since their a posteriori knowledge of the basic period was used, this calculated value of the probability can represent only a lower limit.

A more realistic test of statistical significance is to assume only the total available time range and the total number of observed maxima, N. Although an analytic solution then exists for very large N (Broadbent 1955), Monte Carlo simulations based on the null hypothesis of randomly distributed times can be used for small N, as here. A uniform (or rectangular) distribution is assumed for these random times. We find that such random time series yield high spectral peaks (higher than the observed spectral peak of the basic discovered period) anywhere over the trial period range 7–100 yr in 12% of the cases for $N = 7$ (time range taken between 1910 and 1996) or in 2% of the cases for $N = 6$ (time range taken between 1931 and 1996). Since the $N = 6$ simulations are more realistic than the $N = 7$ ones, owing to the possibility of a missing 1925 maximum, the estimate for $N = 6$ is more appropriate, and hence one might reject the null hypothesis of randomness at the 2% significance level. On the other hand, this result is not so strong that OJ 287 could not be regarded as simply quasi-periodic or even nonperiodic. Such a conclusion is reinforced by the realization that if the assigned trial periods are extended below 7 yr, the percentages derived above become *larger*.

It would probably be very difficult to properly design a significance test for the basic period using the full light curve. The reason is that the observed data points are distributed in a very inhomogeneous manner.

6. DISCUSSION

The well-defined pulses in OJ 287, together with the reasonably good time coverage, make this quasar uniquely suited for accurate time series analysis. The only other quasar with a comparably long record of observations is 3C 273, but the pulses are not as clear for this object, and quasi-periods, if they exist at all, seem to occur within the broad range 6–20 yr (Jurkevich 1972; Angione & Smith 1985). This range of quasi-periods appears to be typical of other quasars as well (Angione 1973; Webb et al. 1988). Higher quality data and a longer baseline might strengthen the case for periodicity in some of these less well observed objects. It is worth recalling that, before the data had significantly improved for OJ 287, this quasar was thought to be, at best, only roughly quasi-periodic, with cycle lengths of anywhere from 7 to 40 yr (Visvanathan & Elliot 1973; Gaida & Röser 1982).

Supposing that the 12 yr periodicity in OJ 287 is real, what could cause it? Recent models of blazars have involved either a single or a binary supermassive black hole sporadically accreting matter from a surrounding disk and powering a relativistic jet that is directed toward the observer. Periodicity might arise from pulsation of the accretion disk, from the disk's rotation, or, if the central engine is a pair of supermassive black holes, from orbital motion of the binary system. Owing to difficulties with the expected timescales and disk temperatures, the first two explanations now seem unlikely (Webb et al. 1988). In the more promising binary model, the observed light variations originate from tidally induced mass flows out of the accretion disk (or disks) and into the two black holes (Begelman, Blandford, & Rees 1980; Sillanpää et al. 1988). This model need not lead to an absolute clockwork periodicity, because the actual mass flows would probably not be triggered precisely at periastron but maybe a bit before or after. Therefore, a seeming quasi-periodicity with an underlying *constant mean period* is expected. Only a much longer series of observations will reveal whether the present 12 yr periodicity is maintained. Note that accretion into the *two* black holes could explain the double-peak characteristic of the light maxima. The model also predicts precession of the relativistic jet (or jets), which might account for the ~54 yr modulation period of the light curve (Sillanpää et al. 1996). Evolution of the orbit would eventually create a measurable secular change in the basic 12 yr period itself.

Regardless of the plausibility or implausibility of the suggested physical model, an underlying deterministic statistical model for the observed light curve is supported by the recent success of a set of predictions for the 1994 outburst (Sillanpää et al. 1988, 1996; Kidger et al. 1992). These predictions included the timing of the burst's start at some time during 1994, its small amplitude, and the subsequent secondary light maximum about 1 year later.

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